

## PL611s-02/-04 Frequency Fine Tuning Mathematics

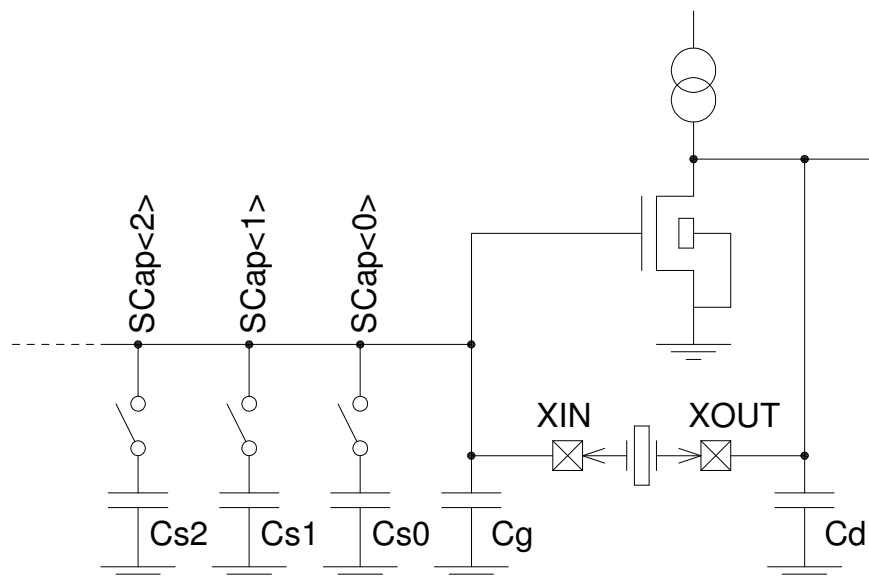
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The PL611s-02 and PL611s-04 have a programmable load capacitance (CL). This programmable CL can be utilized to fine tune the final output frequency of a clock oscillator module that uses the PL611s-02/-04. This application note describes a method with supporting mathematics for how to implement the frequency fine tuning.

### Crystal Oscillator Schematic



The PL611s-02/-04 has one address with 8 bits (SCap<7:0>) to control the load capacitance. Through these SCap bits, capacitors Cs0 ~ Cs7 can be turned on or off. The final CL value of the crystal oscillator is a function of the SCap switches. With the SCap switches the CL value can be varied roughly between 8pF and 12pF. The values for the capacitors are as follows:

Cd = 24pF , fixed capacitance at the “drain” of the oscillator transistor.

Cg = 10pF , fixed capacitance at the “gate” of the oscillator transistor.

Cs0 = 0.04pF , Cs1 = 0.08pF , Cs2 = 0.16pF , Cs3 = 0.32pF , etcetera up to Cs7 = 5.12pF.

The total CL value is:  $CL = (Cd \times (Cg + Cs)) / (Cd + Cg + Cs)$

Cs represents the capacitors Cs0 ~ Cs7 that are turned on through the SCap bits.

When the chip is used in an application there is always parasitic capacitance. Including a parasitic capacitance Cp from each crystal pin to ground, the formula for the total CL becomes like this:

$CL = ((Cd + Cp) \times (Cg + Cs + Cp)) / (Cd + Cg + Cs + 2Cp)$

**PL611s-02/-04 Frequency Fine Tuning Mathematics****Frequency Fine Tune Method**

When the PL611s-02/-04 is not yet programmed, it operates in a test mode where the SCap<7:0> code is "01100000". This setting makes a CL value of 9.3pF with Cp=1pF. After programming the "testb" bit, this test mode will disappear and the CL value will change to its minimum value of 7.6pF (Cp=1pF). We can measure the crystal frequency at these two instances with CL1=9.3pF and CL2=7.6pF and calculate an SCap setting that tunes the frequency as close as possible to our target (0 ppm).

Unfortunately, only programming "testb" does not result in a stable output frequency because the PLL settings are invalid (all counters are zero). Additional to "testb" it is also advised to program all other settings for the intended final function and output clock frequency of the PL611s-02/-04.

The sequence is as follows:

- Measure FL1 (we know CL1=9.3pF).
- Program "testb" and all other settings, except SCap settings and the "opmode" bit.
- Determine FL2 (we know CL2=7.6pF). Measure the clock frequency and calculate FL2 from the known counter values.
- Calculate the optimum SCap settings.
- Program SCap bits and "opmode" bit to finalize programming.

**Frequency Fine Tune Mathematics**

The two frequencies FL1 and FL2 will tell us two things:

- 1) Where is the clock frequency in relation to the target.
- 2) What is the tuning sensitivity. In other words, how much does the frequency change per bit of change with the SCap setting.

The mathematics tries to calculate the crystal parameters from the FL1 and FL2 results and with this information the optimum SCap setting can be determined.

The general formula for FL as a function of CL is as follows:  $FL = F_s \times \text{SQRT}(1 + C1/(C0+CL))$

FL is the "Load Frequency" or the frequency where the crystal oscillator will operate.

CL is the "Load Capacitance".

Fs is the series resonance frequency of the crystal.

C1 is the motional capacitance of the crystal.

C0 is the parallel or shunt capacitance of the crystal.

We have to solve the equations for these two situations:

- 1)  $FL1 = F_s \times \text{SQRT}(1 + C1/(C0+CL1))$
- 2)  $FL2 = F_s \times \text{SQRT}(1 + C1/(C0+CL2))$

There is a problem with this situation: we have two equations and three unknown parameters: Fs, C1 and C0. Fortunately with a quartz crystal the ratio between C0 and C1 is fairly constant at about 250. Lets introduce a ratio as a constant  $R = C0 / C1$ .

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The two equations can be taken together to eliminate Fs:

$$(FL1/FL2)^2 = (1 + C1/(C0+CL1)) / (1 + C1/(C0+CL2))$$

$$(FL1/FL2)^2 = (1 + C1/(R \times C1 + CL1)) / (1 + C1/(R \times C1 + CL2))$$

Working all this out we arrive at the following 2<sup>nd</sup> order formula:

$$R \times (R+1) \times ((FL1/FL2)^2 - 1) \times C1^2 +$$

$$\{ (FL1/FL2)^2 \times ((R+1) \times CL1 + R \times CL2) - R \times CL1 - (R+1) \times CL2 \} \times C1 +$$

$$((FL1/FL2)^2 - 1) \times CL1 \times CL2 = 0$$

We can solve this equation with the standard formula  $C1 = (-b + \text{SQRT}(b^2 - 4ac)) / 2a$ , where:

$$a = R \times (R+1) \times ((FL1/FL2)^2 - 1)$$

$$b = (FL1/FL2)^2 \times ((R+1) \times CL1 + R \times CL2) - R \times CL1 - (R+1) \times CL2$$

$$c = ((FL1/FL2)^2 - 1) \times CL1 \times CL2$$

Knowing C1 we can calculate  $C0 = R \times C1$ .

Knowing C1 and C0 we can calculate  $Fs = FL1 / \text{SQRT}(1 + C1/(C0 + CL1))$

Lets call the target frequency "FLT" and the corresponding Load Capacitance "CLT":

$$FLT = Fs \times \text{SQRT}(1 + C1/(C0 + CLT))$$

This can be rewritten as follows:  $CLT = C1 / ((FLT/Fs)^2 - 1) - C0$

We know the target frequency so this formula will give us the CL value we need to program to achieve the target frequency.

Lets solve the rest of the mathematics in steps:

Eliminate Cd:  $Ca = CLT \times (Cd + Cp) / (Cd + Cp - CLT)$

Eliminate Cg:  $Cs = Ca - Cg - Cp$

To find each SCap bit we can follow the following programming method:

FOR x=7 TO 0 STEP -1

$$y = 0.04\text{pF} \times 2^x$$

IF  $Cs < y$  then

$$\text{SCap}\langle x \rangle = 0$$

ELSE

$$\text{SCap}\langle x \rangle = 1$$

$$Cs = Cs - y$$

END IF

NEXT x

## PL611s-02/-04 Frequency Fine Tuning Mathematics

### Frequency Fine Tune Example

The following is an example for how the mathematics can be used to find the optimum SCap settings.

For this example we use a clock oscillator module with the PL611s-02 or PL611s-04 and a 25MHz crystal. The unprogrammed module output frequency reads 25.000321MHz (+12.8ppm).

Next we program the module with settings to make a 100MHz output clock but we leave the SCap settings at all zeros. The counter settings are R=5, M=40 and P=2. The formula for the output frequency is as follows:  $F_{out} = F_{xtal} \times M / (P \times R) = 25 \times 40 / (2 \times 5) = 100$ .

When we measure the frequency we see 100.006423MHz (+64.2ppm). Calculating backwards we find the crystal frequency is 25.001606MHz (+64.2ppm).

So we know the following:

FL1 = 25.000321MHz with CL1=9.3pF.

FL2 = 25.001606MHz with CL2=7.6pF.

Lets use  $R = C0/C1 = 250$ .

$$a = R \times (R+1) \times ((FL1/FL2)^2 - 1) = 250 \times 251 \times ((25.000321/25.001606)^2 - 1) = -6.4501200$$

$$b = (FL1/FL2)^2 \times ((R+1) \times CL1 + R \times CL2) - R \times CL1 - (R+1) \times CL2$$

$$b = (25.000321/25.001606)^2 \times (251 \times 9.3 + 250 \times 7.6) - 250 \times 9.3 - 251 \times 7.6 = 1.2647531$$

$$c = ((FL1/FL2)^2 - 1) \times CL1 \times CL2 = ((25.000321/25.001606)^2 - 1) \times 9.3 \times 7.6 = -0.0072652507$$

$$\text{Crystal } C1 = (-b + \text{SQRT}(b^2 - 4ac)) / 2a = 0.005923\text{pF}$$

$$\text{Crystal } C0 = 250 \times C1 = 1.4808\text{pF}$$

$$\text{Crystal } Fs = FL1 / \text{SQRT}(1 + C1 / (C0 + CL1)) = 24.993456\text{MHz}$$

Our target frequency FLT is 25.000000MHz.

$$CLT = C1 / ((FLT/Fs)^2 - 1) - C0 = 9.829\text{pF}$$

$$\text{Eliminate } Cd: Ca = CLT \times (Cd + Cp) / (Cd + Cp - CLT) = 9.829 \times (24 + 1) / (24 + 1 - 9.829) = 16.197\text{pF}$$

$$\text{Eliminate } Cg: Cs = Ca - Cg - Cp = 5.197\text{pF}$$

6.367pF is bigger than 5.12pF so SCap<7>=1, remaining is 5.197-5.12 = 0.077pF

Remaining is smaller than 2.56pF so SCap<6>=0

Remaining is smaller than 1.28pF so SCap<5>=0

Remaining is smaller than 0.64pF so SCap<4>=0

Remaining is smaller than 0.32pF so SCap<3>=0

Remaining is smaller than 0.16pF so SCap<2>=0

Remaining is smaller than 0.08pF so SCap<1>=0

Remaining is bigger than 0.04pF so SCap<0>=1

So the optimum SCap setting is: SCap<7:0> = 10000001.